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TURBULENCE CHARACTERIZATION AND CONTROL

M. G. Miller, et al

Avco Everett Research Laboratory, Incorporated

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TURBULENCE CHARACTERIZATION AND CONTROL

Avco Everett Research Laboratory, Inc.

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TURBULENCE CHARACTERIZATION AND CONTROL

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This report covers some aspects of our investigations of atmospheric turbulence effects related to optical imaging. Three specific subjects are discussed. The first is the initial seeing survey carried out in 1962-63 at the ARPA Maui Observation Station (AMOS) on the summit of Haleakala, Maui, Hawaii. These measurements involved the visual observation of planetary features using a 12.5" Newtonian reflector. Seeing was rated on an arbitrary scale of 0 to 10 and then related to angular resolution in some unknown

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) fashion. After study of the available documents, we conclude that the survey, while suggesting, does not strongly support the conclusion that the presence and/or operation of the observatory has disturbed the excellent natural seeing characteristics which may have existed at the site.

In order to provide additional information on this subject we carried out a series of measurements of the differential angle of arrival variance at AMOS during August 1974. Stellar sources, a seven inch telescope and a Hartmann test procedure were used to collect the data. Our results for the differential standard deviation ranged from 2 to 9 μ rad with a mean of 4.3 μ rad. In the report we discuss the technique, underlying theory and obtain estimates of related atmospheric parameters. A discussion of the utility of this type of measurement for estimating the resolution capability of optics of arbitrary size is also included.

The final subject is a study of local turbulence control practices used by the astronomical community. We conclude that a set of methods and recommendations are generally recognized as useful. However it does not appear that the utility or universality of any single method is clearly understood. Present practice at AMOS does take advantage of some of these methods. Others could be instituted in a straightforward manner. In particular, we recommend that forced air low test be implemented and carried out in conjunction with the series of atmospheric characterization tests scheduled for late summer and/or early fall, 1975.

PREFACE

The work reported here is part of an overall ARPA/RADC program to evaluate and characterize atmospheric turbulence, both natural and local, at AMOS. Reports of related work and comparisons of experimental results will be found elsewhere.

We would like to thank the AMOS staff, in particular Mr. Paul Zieske, for assistance during the experimental portions of this effort. Messrs. Joe Heath and Herb Kent were major sources of information on the control of local turbulence. Heath considered this problem under Contract F04701-72-C-0082 to the Lockheed Missiles and Space Company, Inc. Kent's work was funded under Contract F04701-72-C-0081 to Avco Everett Research Laboratory, Inc.

Finally, we acknowledge Applied Optics for permission to reproduce Figure 1.

SUMMARY

This report covers some aspects of our investigations of atmospheric turbulence effects related to optical imaging. Three specific subjects are discussed. The first is the initial seeing survey carried out in 1962-63 at the ARPA Maui Observation Station (AMOS) on the summit of Haleakala, Maui, Hawaii. These measurements involved the visual observation of planetary features using a 12.5" Newtonian reflector. Seeing was rated on an arbitrary scale of 0 to 10 and then related to angular resolution in some unknown fashion. After study of the available documents, we conclude that the survey, while suggesting, does not strongly support the conclusion that the presence and/or operation of the observatory has disturbed the excellent natural seeing characteristics which may have existed at the site.

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The final subject is a study of local turbulence control practices used by the astronomical community. We conclude that a set of methods and recommendations are generally recognized as useful. However it does not appear that the utility or universality of any single method is clearly understood. Present practice at AMOS does take advantage of some of these methods. Others could be instituted in a straightforward manner. In particular, we recommend that forced air low test be implemented and carried out in conjunction with the series of atmospheric characterization tests scheduled for late summer and/or early fall, 1975.

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1.0 INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES

It is well known that atmospheric turbulence has a significant degrading effect on optical imaging through large aperture telescopes. There are a variety of techniques being investigated whose common objective is to overcome this degradation and restore the image information to diffraction limited quality. Some techniques involve post detection data processing, others are interferometric in nature and a third group attempt to measure the atmospheric phase distortions and correct for them in real time. This latter class, referred to as predetection compensation, are presently receiving extensive study.

A common area of concern to all techniques is the nature of the phase and amplitude distortions induced by random atmospheric turbulence. In order to define these effects, ARPA/RADC has decided to fund a variety of programs, the objective of which is to characterize atmospheric turbulence. In addition to natural turbulence, local turbulence created by the observatory is of interest. If local effects are significant, it may be possible to identify methods of minimizing them.

This program, Turbulence Characterization and Control, involves the collection, processing, analysis and interpretation of a variety of data relative to atmospheric seeing effects taken at the ARPA Maui Observation Station (AMOS) at the summit of Haleakala on the island of Maui, Hawaii. The main objectives of the program are:

- Provide information relative to large aperture imaging systems
- Obtain information of use for specifying and operating a compensated imaging system
- Investigate local turbulence effects and identify techniques for minimizing them if they exist.

A secondary objective is to supply sufficient data to provide a base for comparison with theoretical predictions and a long term characterization of the site. Such data should allow the evaluation of atmospheric turbulence effects on other types of instruments operated at AMOS.

Specific tasks are:

- Processing and analysis of data collected with the Itek Real-Time Atmospheric Measurements System (RTAM)

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- Processing and analysis of data collected with the Hughes Seeing Monitor (SM)
- Assistance in planning, interpretation and correlation of data taken with other instruments
- A study of local turbulence effects including:
  - a) A study of the site survey carried out in 1962 - 1963
  - b) The design and execution of a comparative, quantitative experiment to evaluate these effects
  - c) Analysis of control methods if a problem is found to exist.

The RTAM is an instrument to be mounted on a telescope which utilizes a variable shearing interferometer and a stellar source in order to measure the atmospheric-telescope optical transfer function, both modulus and phase, in two orthogonal directions. These measurements can be made with a one millisecond scan time and a minimum repetition interval of four milliseconds. Hence each scan should represent a single realization of the random atmosphere. The output signals are in analog form suitable for recording on magnetic tape. Data processing software is required in order to determine a number of statistical parameters of the OTF. In particular these include first order statistics (mean and variance) and second order spatial and temporal auto and cross correlations. From this information an atmospheric seeing angle and characteristic time can be defined and determined. Experimental plans call for an investigation of scaling with various parameters such as wavelength, bandwidth, elevation angle and aperture size. Comparisons with theory and other measurements are also to be carried out.

The SM is a device which uses a spinning reticle photometer with a continuously varying frequency to scan the image of a star in the focal plane of the telescope. This yields a measure of the modulus of the OTF (i. e., MTF) with a one millisecond scan and repetition time in two orthogonal directions. While the complete MTF is available in analog form, the SM also provides two digital numbers (one for each axis) which characterize the angular size of the image. This angular characterization is to be processed for mean, variance, cross correlation and temporal correlation functions. This last function can be used to define an atmospheric characteristic time. Studies of parametric variations and various theoretical and experimental comparisons are included in the analysis.

Other site characterization experiments which have or will be carried out at AMOS are the following. The acoustic sounder, a monostatic acoustic backscatter experiment, measures the returns from density fluctuations over the lower 1000 ft. of the atmosphere. Microthermal sensors measure local small scale temperature fluctuations. The data from both of these experiments can be used to obtain a measure of the strength of the index of refraction fluctuations which are of direct interest to optical propagation. Another instrument measures intensity scintillations associated with a stellar source. By using spatial filtering techniques, vertical resolution can be obtained leading to estimates of turbulence strengths at various heights above the ground. While data collection and processing for these instruments are not specifically covered under the contract, interface, assistance in planning, and correlation of results with other data is included in order to maximize the useful output of all data relevant to site characterization.

The final area covered by this contract is the investigation of local turbulence effects. The fundamental question here is the extent to which local effects due to the existence and/or operation of the observatory contribute to the turbulence environment at AMOS. Because the opinion is often expressed that a strong local effect does exist, a key part of this investigation is a study of the original survey of seeing characteristics carried out at the site in 1962 - 1963. The objective of this work is to determine if the above conclusion is supported. In order to provide additional data a new set of experiments have been undertaken. The microthermal sensors mentioned above provide useful data of this type. In additiona an optical experiment capable of making quantitative, comparative measurements has been designed and a series of measurements carried out and reduced. The final part of this effort is to determine methods of controlling local effects if they are found to make a significant contribution to the overall environment.

1.2 STATUS

As of the date of this report, SM and RTAM data has not been available for reduction. Therefore all efforts relative to these instruments has been confined to obtained an understanding of their basic operation, interface activities and defining the data recording and processing requirements.

Relative to the third task, a number of meetings have been supported. These meetings have been with RADC and AMOS personnel as well as with other contractors involved in the site characterization and compensated imaging programs. The main subject of these discussions has been interface activities, scheduling and experimental planning.

Considerable activity on all three parts of the local turbulence task has been carried out. A number of reports relative to the initial site survey have been located and studied. A discussion of this subject is given in Section 2.0 of this report.

An optical experiment based on the measurement of angle of arrival fluctuations via a Hartmann test procedure has been designed and implemented. A series of measurements were carried out at AMOS during August 1974. In all, twenty reducible data sets were collected. Reduction and analysis of these data has been completed. During some of these experimental runs, microthermal and acoustic sounder data was also collected by RADC and AFCRL personnel. A complete discussion of the experiment, data reduction, and results is given in Section 3.0.

Study of local effects control methods has been confined to a literature survey in order to determine techniques used by the astronomical community. A summary of these practices is given in Section 4.0. Major sources of this information were J. Heath and H. Kent of the AERL AMOS staff. Heath considered this problem while an employee of the Lockheed Missiles and Space Company (AMOS Phase II Operations and Maintenance Contractor). Kent carried out his studies while working on the AMOS Phase II Scientific and Technical Direction contract.

1.3 RESULTS AND CONCLUSIONS

We now have the following information about the initial survey of AMOS seeing characteristics.

- The survey was carried out by A. K. Herring under the direction of G. P. Kuiper, both of the University of Arizona.
- The method employed was a visual observation of various planets with a 12.5" Newtonian reflector.
- Seeing was rated on an arbitrary scale of 0 to 10 (worst to best).
- The measurements were qualitative.
- The method by which these measurements were related to angular resolution is unknown.

Based on this information, we have arrived at the following tentative conclusion.

- The survey, while suggesting, does not strongly support the conclusion that sub arc second seeing existed at Haleakala prior to building AMOS and was significantly degraded by the presence and/or operation of the observatory.

From the reduction of angle of arrival information we have the following results.

- The twenty measured angle of arrival variances ranged from 2 to 9 μrad with a mean of 4.3 μrad.
- Theoretically derived values of the Mutual Coherence Function correlation scale, r_o, ranged from 3 to 18 cm with a mean of 10.3 cm for vertical propagation.
- Night-to-night variations were generally larger than variations over a single night.
- The results are not consistent with a strong local effect.

A study of turbulence control practices used by the astronomical community yields the following information.

- A set of methods and recommendations are generally recognized as useful.
- It does not appear that the utility and universality of any single method is clearly understood.
- A general feeling exists that thermal control (positive control of air flow) is of major importance.
- Present practice at AMOS does take advantage of some of these recommendations.
- Others could be instituted at low cost in a straightforward manner.

1.4 FUTURE PLANS AND RECOMMENDATIONS

Development of the processing software required for the SM and RTAM will begin during the next quarter. It is now anticipated that data from these two instruments will become available during the last quarter of this contract. Hopefully the amount of data and time available will be sufficient to validate the data reduction algorithms.

Because the information obtained to date on the initial survey is incomplete, efforts to locate additional documentation will be continued. The major remaining question is the manner in which angular resolution was associated with these measurements. The information is required in order to allow a valid comparison between the original data and the data collected in this (and other) programs.

Current scheduling calls for another experimental run using all of the instruments discussed in Section 1.1 during the late summer of 1975. However, for a variety of reasons it now appears that this schedule may slip into the fall. Because of the generally positive results obtained in August 1974, we recommend that an angle of arrival data collection period be carried out in the early summer in addition to the late summer or fall series. These experiments can be run in conjunction with microthermal sensors which should be installed and operational at the site in the near future. There also exists a portable 8-inch aperture telescope at AMOS. For a modest cost this telescope could be equipped with the necessary relay optics and camera which would allow simultaneous collection of angle of arrival data at two different locations. Concurrent with these activities we are investigating methods for automating the data reading and processing. The time consumed in the presently used methods represent the major drawback to the technique.

At present, no future activity in identifying methods of controlling local turbulence effects is planned until their existence is clearly established. However we recommend that forced air flow test (as discussed by Heath) be implemented. An ideal time to carry out these tests would be during the late summer or fall series. This would allow a quantitative measure of the results by using other available instrumentation such as the SM or RTAM.

2.0 AMOS SEEING - INITIAL SITE SURVEY

2.1 GENERAL

Since the establishment of the AMOS observatory, an attitude has arisen that while an initial survey showed Haleakala to be a site with excellent seeing characteristics, little or no data has been obtained at AMOS which matches these expectations. The conclusion which is inferred (at least informally) is that due to the physical structures and/or the operation of the observatory, a strong local turbulence effect has been generated which has negated the excellent natural characteristics. The purpose of this section is to examine (as much as possible) the survey data and determine if it supports this conclusion.

2.2 INITIAL SURVEY-RESULTS

It appears that the most widely circulated data relative to AMOS seeing is an article by Zirkind[1] in which seeing characteristics are plotted as a function of time. This data is given in Figure 1. As can be seen, for each night of observation a range (min to max) and average are given. In total, 72 nights over a period of approximately ten months are summarized. Three scales are given. One in arbitrary units from 1 to 10 (bad to good). The AURA equivalent, an empirical scale related to the visual appearance of a star image. Finally, an angular scale in arc seconds. Zirkind attributes this data to G. P. Kuiper (of the University of Arizona) and informally references a seeing report prepared by the University of Arizona. The data shows 53 measurements with average seeing better than 0.5 arc sec. In only nine cases was the average value larger than 1.0 arc sec while in nine other cases the average was smaller than 0.2 arc sec. In comparison, subjective observations (and some quantitative data) since the site became operative indicate seeing to be more typically one or more arc seconds with occasional sub arc second operation. These contrasting values are the data which had lead to the conclusion given in the first section. However before accepting this conclusion the situation requires further examination. Key questions are:

1) What was the nature of the survey experiments?

2) What kind of instrument was used?

3) Which of the three scales of Zirkind's graph was used in the survey?

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[1] R. Zirkind, App. Opt. 4, 1077 (1965).

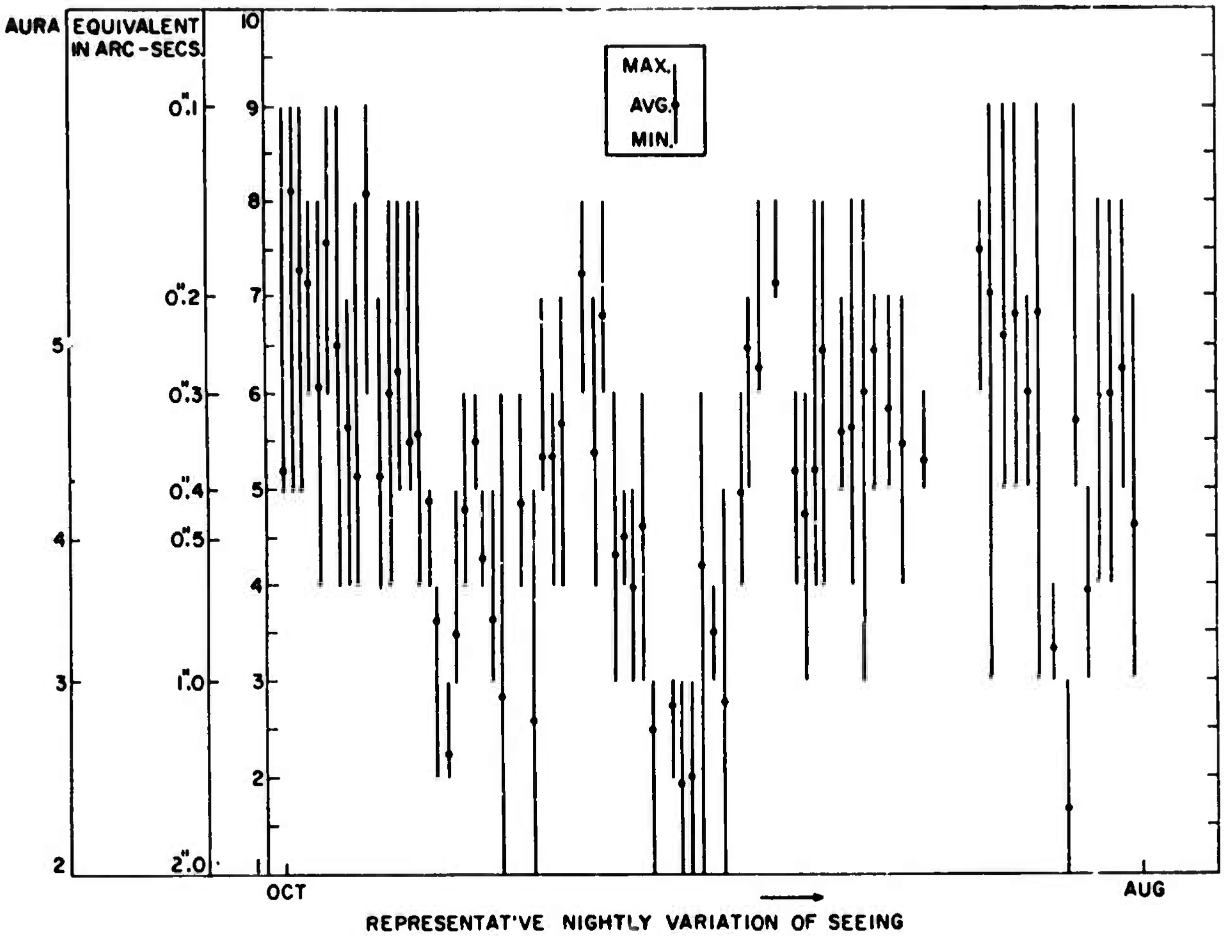

Figure 1 AMOS Seeing - Initial Survey

4) How was the relative placement of the three scales established and by whom?

5) Are the results quantitative?

2.3 INITIAL SURVEY-DESCRIPTION

The University of Arizona report informally referenced by Zirkind has not been located. However several other references have been[2,3]. Both of these are University of Michigan reports (Project AMOS reports). The latter report includes a brief reference while the earlier one contains portions of reports (apparently informal letter type) to the University of Michigan by University of Arizona personnel.

Based on these two reports we have the following information. The survey was carried out by A. K. Herring and perhaps E. Whitaker of the University of Arizona under the direction of Kuiper who visited Haleakala at least once (Nov. 10-17, 1962). The survey started about October 22-26, 1962 and continued until August 1963 (based on Zirkind graph). However reports attributed to Herring and Kuiper cover only the period of October-November 1962.

The survey was based on visual observations of Mars, Jupiter, Saturn and the Moon using a 12.5" Newtonian reflector designed by Herring. The site of these observations were the 18-foot dome of the University of Hawaii Solar Observatory. A second telescope of six-inch aperture may also have been used in order to investigate relative seeing at different locations. Seeing was estimated on a scale of zero to ten (worst to best) with the statement that 0-2.5 was poor, 2.5-5.0 was fair, 5-7.5 was good and 7.5-10.0 was excellent. Successful measurements were made on 78 of 114 attempts. On 11 nights the best seeing was 9 and on 19 nights it was 8. Except for the total number (78), these values are the same as shown by Zirkind.

It is of interest to quote portions of Herring's first report (made on the basis of 47 estimates between October 26 and November 3, 1962). With regard to seeing he said: "For the most part, the seeing conditions were from good to excellent, and were often superb . . . some seeing . . . might be considered as only fair, the amount was small . . . At no time was the seeing really poor . . . very good by Tucson standards." In summary he says: "My conclusion, tentative of course, . . . is an extremely good location for an astronomical observatory . . . far superior to the Catalina site . . ."

[2,3]These references are available to qualified military and government agencies on request from RADC (OCSE) Griffiss AFB NY 13441.

With regard to the measurements he writes, "The enclosed graph . . . of seeing estimates . . . . While it is not quantitative, it is qualitative . . . ."

And finally with respect to his observations of Jupiter (apparently his specialty) ". . . made some drawings that I think are going to be the best ever made. It is certainly a rare privilege . . . to use my telescope under conditions that give me 80 to 90% efficiency almost all the time."

In Kuiper's report of his trip to Haleakala he says: ". . . the seeing scale adopted by Mr. Herring agrees very closely with my own, which . . . agrees with that of other visual observers . . . . The seeing was never found to be distinctly bad, although average quality does occur approximately half the time."

Other comments made by Herring and Kuiper indicate a degradation of conditions with time over a single night. Also a "definite correlation" with wind direction, seeing being poorer for tradewind patterns.

The later University of Michigan report states that these measurements led the recommendation that ". . . in order to take advantage of the periods of superlative seeing conditions, a high-quality telescope of at least 60-inch free aperture should be used."

2.4 DISCUSSION AND CONCLUSIONS

While the documents uncovered to date are incomplete, we believe they are sufficient to come to some conclusions regarding the key questions. However, we shall continue to look for the University of Arizona report which may contain a more complete description.

Relative to the first three questions, we now know that the experiments were visual observations of planets. The instrument used as a 12.5-inch telescope which has a Rayleigh resolution limit ($1.22\ \lambda/D$) of 0.4 arc seconds at $\lambda = 0.55\ \mu m$. The scale used in the survey was an arbitrary one with units of zero to ten, apparently the one to ten scale shown by Zirkind. No mention of other scales are made in the University of Michigan reports.

As to the placement of the other two scales we have found no information as to the manner in which the relative scales were placed and by whom. However the data does indicate several questions. It would seem difficult to associate measurements down to 0.1 arc sec with a telescope which has a Rayleigh limit of 0.4 arc sec. While the Rayleigh criterion tends to be conservative, a factor of four is a rather large margin. It is also interesting to note that Herring felt he had 80-90% efficiency almost all the time. It is not clear what this statement means but one could speculate that the interpretation is that he was able to obtain near diffraction limited information most of the time, but not sub-diffraction limited.

Finally, the AURA scale[4] is an empirical scale dealing with the observation of binary stars. It is not obvious that estimates based on the observations of planets can be easily correlated with this scale unless it was done by Herring after extensive observations of both types under near identical conditions. Even if this was the case, the correlation between the AURA and arc sec scales is not obvious since the former tends to deal with overall image quality while the latter tends to stress one specific aspect of the image, i.e., overall size.

With regard to the final question, we have both the statement of Zirkind and the statement attributed to Herring that the measurements were qualitative and not quantitative.

In summary, it appears that the site survey of seeing characteristics carried out by Herring under the direction of Kuiper, (at least to the extent of the information we presently have) while suggesting, does not strongly support the conclusion that sub arc second seeing characteristics which existed at Haleakala prior to building AMOS and have been disturbed by the presence and/or operation of the observatory.

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(4) A. B. Meinel, in Telescopes, ed. by G. P. Kuiper and B. M. Middlehurst (University of Chicago, 1962), 154.

3.0 DIFFERENTIAL ANGLE OF ARRIVAL MEASUREMENTS

3.1 GENERAL

Atmospheric turbulence is an important consideration in the operation of any large telescope. While natural turbulence usually imposes a resolution limit of the order of several arc seconds, local effects due to structures and thermal sources can also be important.[4] In order to obtain information about these effects, we designed a portable optical experiment and carried out a set of measurements at AMOS during August 1974. The fundamental parameter we measured was the angle of arrival of a wave received by a telescope from a stellar source. Turbulence produces a random variation in this quantity. If defined as the direction of the wave normal at the receiving point,[5] the angle of arrival is independent of equipment considerations and is directly proportional to the spatial derivative of the turbulence produced phase fluctuations. For an interferometer, the phase difference between two points separated by the interferometer spacing is the governing quantity. For a telescope, this angle is closely related to the linear tilt of the wave across the aperture. A study of angle of arrival fluctuations isolates and yields a measure of phase effects which can be considered to be complimentary to amplitude effects measured via scintillation studies. Kerr et al[6] have tabulated theoretical values of its variance for a variety of cases. Several measurements over near horizontal paths have been made[7,8]. However, we know of only a single series of measurements[9] made over near vertical slant paths through the entire atmosphere.

We discuss our technique and the underlying theory in the next section. A description of the equipment and measurement procedure is given in Section 3.3. The data processing and error analysis are described in Section 3.4. Our results, discussion and conclusions are given in Section 3.5.

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(5) J. W. Strohbehn and S. F. Clifford, IEEE Trans., AP-15, 416 (1967).

(6) J. R. Kerr, P. J. Titterton, A. R. Kraemer and C. R. Cook, Proc. IEEE 58. 1691 (1970).

(7) A. S. Gurvich and M. A. Kallistrotova, Radiofizika 11, 66 (1968).

(8) A. S. Gurvich, M. A. Kallistrotova and H. S. Time, Radiofizika 11, 1360 (1968).

(9) W. G. Lese, Stellar Image Excursions Cuased by Random Atmospheric Refraction, Ballistic Res. Lab. Memo. Report #2014 (Aberdeen Proving Ground, Md., 1969).

3.2 EXPERIMENTAL TECHNIQUE AND ANALYSIS

The principle requirements placed on the experiment were the ability to produce short exposure, quantitative results with a portable instrument. Short exposure was required in order to obtain statistical information from which a variety of parameters could be obtained. Quantitative results were required so that subjective observations could be avoided. A portable instrument allowed data to be collected at various points in and about the observatory. An additional requirement which was very desirable was the ability to relate the results to large aperture resolution. A number of techniques can lead to this kind of information. We decided to measure the angle of arrival fluctuations over a small aperture. A simple analysis of the basic effect is as follows:

Consider a wave propagating from a distant point source, through the atmosphere and telescope to an image plane. The image plane intensity is given by:

$$I_I(\underset{\sim}{x}) \sim \left| \int d\underset{\sim}{v}\, W(\underset{\sim}{v})\, A(\underset{\sim}{v}) \exp\left\{ -ik\underset{\sim}{x} \cdot \underset{\sim}{v}/R + i\,\phi(\underset{\sim}{v}) \right\} \right|^2 , \qquad (1)$$

where $W(\underset{\sim}{v})$ is the pupil function (assumed real) and $A(\underset{\sim}{v})$ and $\phi(\underset{\sim}{v})$ are the aperture plane amplitude and phase distortion generated by the atmosphere. k is the wave number and R is the telescope focal length. Provided the aperture is small compared with the characteristic scale of the phase fluctuations, $\phi(\underset{\sim}{v})$ can be approximated by the first two terms in a Taylor Series expansion yielding

$$I_I(\underset{\sim}{x}) \sim \left| \int d\underset{\sim}{v}\, W(\underset{\sim}{v})\, A(\underset{\sim}{v}) \exp\left\{ -ik\left[\underset{\sim}{x}/R - \underset{\sim}{\nabla}\phi(o)/k \right] \cdot \underset{\sim}{v} \right\} \right|^2 , \qquad (2)$$

where $\underset{\sim}{\nabla}\phi(o)$ is the spatial derivative of the atmospheric phase evaluated at the center of the aperture. Equation (2) indicates that under these conditions, the image intensity is approximately equal to a distorted Airy pattern with center at

$$\underset{\sim}{x}_c = R\underset{\sim}{\nabla}\phi(o)/k \simeq R\underset{\sim}{\alpha} , \qquad (3)$$

where $\underset{\sim}{\alpha}$ is the angle of arrival, i.e., the angle between the true and apparent direction of the star at the center of the aperture. Hence by observing the motion of a star image through a telescope of small aperture, we can obtain data on atmospheric angle of arrival fluctuations.

There is at least one difficulty with tracking the motion of a single image. The position of the image depends on telescope tracking and wind loading which cannot be separated from turbulence effects. A convenient way to overcome this problem is to equip the telescope with an aperture mask containing two (or more) holes. While at focus the light from all such holes converges nominally to the same point, a small amount of defocus will separate the light into a Fresnel pattern of the aperture mask. This is the approach we have taken in the measurements reported here. It has been suggested previously[10] and is basically a classical Hartmann[11] test procedure. However, instead of analyzing a single long exposure, a series of short exposure data frames are processed for differential motion.

Modifying the analysis to the case of differential motion, the time averaged spacing is given by

$$\langle x_1 - x_2 \rangle = (\Delta/R)\, S\,, \tag{4}$$

where Δ is the amount of defocus and S is the separation of the holes in the aperture. The variance of the differential angle of arrival (one component) is given by:

$$\left\langle (\alpha_1 - \alpha_2)^2 \right\rangle = \frac{\left\langle (x_1 - x_2)^2 \right\rangle - \left\langle x_1 - x_2 \right\rangle^2}{R^2 \left[1 - \Delta/R\right]^2}\ . \tag{5}$$

Provided the ratio (Δ/R) is small, the amount of defocus used is not critical for determining the angle of arrival variance.

Assuming mean zero α, the differential variance (single component) is related to the single hole variance (Eq. (3)) by

$$\left\langle (\alpha_1 - \alpha_2)^2 \right\rangle = 2 \left\langle \alpha^2 \right\rangle \left[1 - C_{12}(S)\right]\,, \tag{6}$$

where $C_{12}(S)$ is the normalized correlation function, $\langle \alpha_1 \alpha_2 \rangle / \langle \alpha^2 \rangle$. A theoretical model for Eq. (6) has recently been developed by Fried.[12] The single hole variance is given by[13]

$$\left\langle \alpha^2 \right\rangle \simeq D_\phi(d)/k^2 d^2\,, \tag{7}$$

where d is the hole diameter and $D_\phi(d)$ is the phase structure function defined by $\left\langle \left[\phi(\underset{\sim}{v}) - \phi(\underset{\sim}{v} + \underset{\sim}{d})\right]^2 \right\rangle$.

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(10) See for example: J. Stock and G. Keller, in Ref. 4, 145.

(11) J. Hartmann, Z. Instrum. 24, 100 (1904).

(12) D. L. Fried, Theoretical Study of Non-Standard Imaging Concepts, Report #RADC-TR-74-185 (Rome Air Development Center, Griffiss AFB, N.Y., 1974).

(13) V. I. Tatarski, The Effects of the Turbulent Atmosphere on Wave Propagation (NTIS, Springfield, Va., 1971).

The long exposure optical transfer function which controls the long exposure resolution of a telescope of arbitrary size is given theoretically by[14, 15]

$$\langle \tau(\underset{\sim}{f}) \rangle = \tau_o(\lambda R f) \exp\left[-D(\lambda R f)/2\right], \tag{8}$$

$$D(\rho) = D_l(\rho) + D_\phi(\rho), \tag{9}$$

where f is the spatial frequency, λ is the wavelength, D_l is the atmospheric log-amplitude structure function and τ_o is the telescope (no atmosphere) optical transfer function.

Assuming a Kolmogorov turbulence spectrum and the Rytov approximation[15]

$$D(\rho) = 6.88\,(\rho/r_o)^{5/3} \tag{10}$$

$$D_\phi(\rho) = \beta(\rho)\,D(\rho);\ \beta(\rho) = \begin{Bmatrix} 1/2 \text{ for } \rho \ll \sqrt{\lambda L} \\ 1 \text{ for } \rho \gg \sqrt{\lambda L} \end{Bmatrix}, \tag{11}$$

provided ρ is larger than some small number[16]. L is the pathlength through turbulence. Provided the model assumed is correct we see the differential angle of arrival measurements made with a small instrument (Eq. (5)) can be used to derive values of r_o (Eqs. (6), (7), (10) and (11)) which in turn can be used to predict the resolution capabilities of a telescope of arbitrary aperture (Eq. (8)).

3.3 INSTRUMENT AND MEASUREMENT PROCEDURE

The instument chosen for this experiment was a Questar Seven. This telescope is a Maksutov Cassegrain Catadioptric system with a clear aperture of seven inches, obscuration ratio of 0.34 and a prime focal length of 112 inches. In order to increase the image motion a minus 66.06 mm FL Barlow Lens was used to provide a 2X magnification. The system was equipped with a portable tripod and clock drive in order to provide portability and sidereal tracking. A schematic of the system is shown in Figure 2.

Data was recorded using a modified Nikon F 35 mm camera body equipped with a 250 exposure motorized film drive. However we found that it was necessary to advance the film and release the shutter by hand

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(14) R. E. Hufnagel and N. R. Stanley, J. Opt. Soc. Am. 54, 52 (1964).

(15) D. L. Fried, J. Opt. Soc. Am. 56, 1372 (1966).

(16) R. S. Lawrence and J. W. Strohbehn, IEEE 58, 1523 (1970).

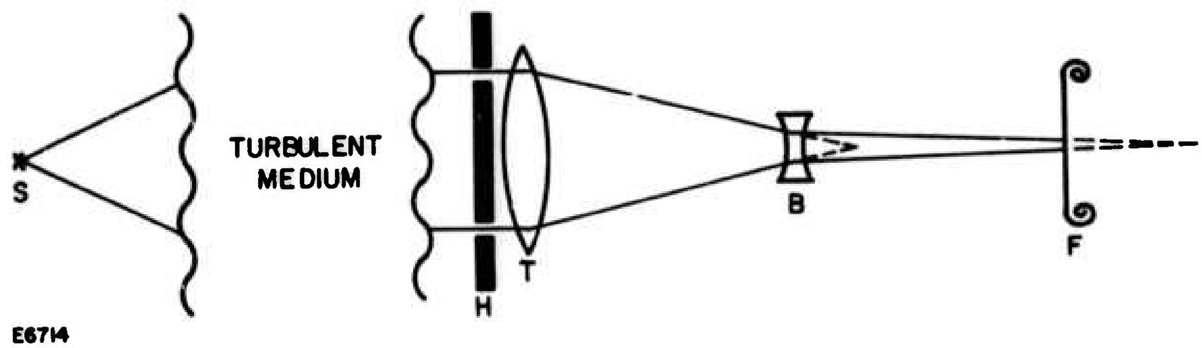


Figure 2 Schematic Diagram of Optical System Showing Source S, Telescope T, Hartmann Plate H, Barlow Lens B, and Film F.

in order to avoid excessive vibration. The film used was Kodak RAR 2484. Processing was carried out for two minutes at 94°F in D-19 developer.

Several different Hartmann plates were built and used in the experiments. However all data reduced corresponded to a plate consisting of two 2.25-inch diameter holes with a separation of 4.75 inches.

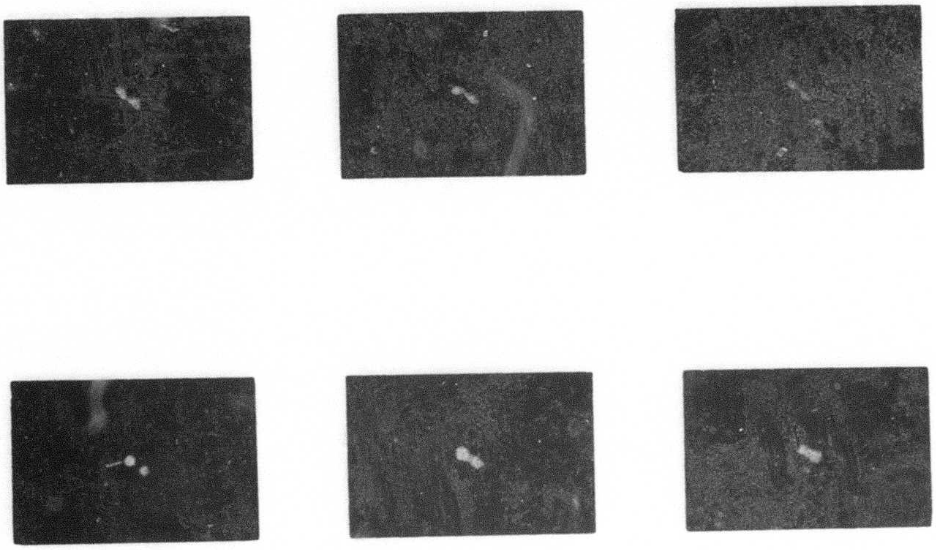
Data was collected at AMOS during the period of 19 August to 31 August 1974. Data was taken at three different locations. Inside the east dome of the observatory, outside at a distance of approximately 50 feet north of the observatory, and atop Red Hill (highest point on the mountain) at a distance of approximately 2000 feet north east of the observatory.

Briefly, the measurement procedure was as follows. The telescope was placed in equatorial configuration, a bright star acquired (Vega or Altair) and sidereal tracking engaged. The amount of defocus was adjusted visually in order to provide good image separation but without an extensive reduction in energy density. A series of short exposure images were then taken with an exposure time of (1/60) second and an interframe time of approximately 5 to 10 seconds. In all, 100-120 data frames were collected in each experimental run. Typical data frames are shown in Figure 3. A summary of all data runs attempted is given in Table 1.

3.4 DATA PROCESSING

Image spacing on each data frame was measured using a David Mann Optical Comparator. This is a device which uses precision lead screws to position cross-hairs on a desired location. Readout is in two dimensional digital format on computer cards or typewriter. The precision of this instrument is 1 μm. The center of each image was estimated visually by by the operator. All readings were reduced to a single differential image spacing. This was done to minimize misalignments and variations which might be associated with the film transport mechanisms and telescope.

In order to determine the reading repeatability and gain an estimate of errors, ten data frames were selected at random and read by two different operators. Ten independent readings on each frame were made. The resulting data was first smoothed by averaging over the ten readings for each frame. The ten frame average and variance (of the smoothed data) were then calculated. The results of this analysis are shown in Table 2. Assuming independent Gaussian read errors, the estimated sigma (due to reading errors) associated with the ten frame smoothed data should be of order 0.5 μm. The estimated sigma associated with the ten frame root variance should be of order 0.4 and 0.8 μm for the two operators, respectively. As can be seen from Table 2, the final results are consistent with these estimates. We note that this analysis does not deal exactly with the quantization error ($\pm$ 1 μm). However, in view of the magnitude of the turbulence induced root variance indicated by the table (> 10 μm), this effect should not be significant.



E6802

Figure 3 Typical Two-Hole Hartmann Data Frames Taken with an Exposure Time of (1/60) Second and 0.7 cm of Defocus. The source was Vega at 72° elevation.

TABLE 1. DATA SUMMARY

Date[1] Time	Data ID	Location[2]	Hartmann[3] Plate	Object; θ El	Comments
8/21 0030	ESNB	Outside	2	Vega	Exposure sequence
8/22 0030	ESB	Outside	1, 3	Vega	Exposure sequence and 25 frames of Hartmann data
8/23 1000	823-1	Outside	1	Vega	No data: vibration in motor drive
8/23 1100	823-2	Outside	1	Vega	No data: vibration in motor drive
8/23 0100		Outside	1	Altair	No data: camera malfunction
8/24 1000	1-1	Outside	1	Vega, 67°	Acoustic and microthermal data
8/24 1100	2-1	Outside	1	Altair, 75°	Acoustic and microthermal data
8/24 1130	2-2	Outside	1	Altair, 68°	Acoustic and microthermal data
8/24 0015	3-1	Outside	1	Altair, 58°	Acoustic and microthermal data
8/25 0945	3-2	Outside	1	Vega, 65°	Acoustic and microthermal data partial data loss due to power failure during development
8/25 1030	4-1	Inside	1	Vega, 58°	Acoustic and microthermal data
8/25 0000	4-2	Inside	1	Altair, 55°	Acoustic and microthermal data only 70 frames due to wrong focus
8/25 0030	5-1	Outside	1	Altair, 48°	Acoustic and microthermal data
8/26 0810	5-2	Outside	3	Vega, 72°	Acoustic and microthermal data
8/26 0845		Outside	1	Vega, 72°	No data: camera malfunction
8/26 0930		Inside	1	Vega, 70°	No data: camera malfunction
8/26 1040	6-1	Inside	1	Vega, 60°	Acoustic and microthermal data only ≈ 90 frames
8/26 1115	6-2	Outside	1	Vega, 54°	Acoustic and microthermal data
8/27 0900	7-1	Outside	2	Vega, 72°	One Hartmann aperture blocked
8/27 0930	7-2	Inside	2	Vega, 69°	Further activity suspended due to power failure
8/29 0830	8-1	Inside	2	Vega, 72°	Wind ≈ 45° off slot
8/29 0930	8-2	Inside	2	Vega, 68°	Wind ≈ 135° off slot
8/29 1000	9-1	Inside	2	Altair, 78°	Slot down wind
8/29 1015	9-2	Inside	2	Altair, 75°	Slot up wind
8/30 0845	10-1	Red Hill	2	Vega, 72°	Outside visitors center, not in wind shadow
8/30 0930	10-2	Red Hill	2	Vega, 68°	Same location as case 10-1
8/30 1045	11-1	Inside	2	Altair, 78°	
8/30 1100	11-2	Inside	3	Altair, 75°	

Notes: (1) Date refers to the start of a nights activities, time is local standard. Therefore, 0100 on 8/23 is actually 0100 on 8/24.

(2) Outside: Aircraft spotters enclosure except for case ESND.
Inside: East dome (60" dome).
Red Hill: Highest point on mountain.

(3) Hartmann plates:
1 - Three 2.25" apertures
2 - Same as 1 with one hole blocked
3 - Six 1.0" apertures

(4) Each data run (except exposure seg.) consists of ≈ 120 frames of data. Exposure time = 1/60 sec. for plates 1 and 2; 1/30 sec. for 3.

TABLE 2. SAMPLE DATA REDUCTION

	Separation (μm)		Standard Deviation (μm)	
	Operator 1	Operator 2	Operator 1	Operator 2
Single Frame No.				
1	348	349	1.9	6.5
2	358	355	4.3	4.4
3	336	331	6.1	3.4
4	335	350	6.2	3.4
5	353	354	4.1	5.4
6	294	298	3.7	5.6
7	375	380	3.7	7.2
8	334	328	4.7	6.4
9	333	326	3.8	6.0
10	318	317	3.3	4.0
Ten Frame Average	338.3	338.8	22.3	22.1

A second check on errors was obtained by processing the same twenty-six data frames on two different occasions (same operator). The data was smoothed by making five independent readings of each frame. The average spacings were 203.0 μm and 204.8 μm, respectively. The standard deviations were 18.4 μm and 17.6 μm, respectively. Because only five readings were taken, the errors associated with these results should increase by a factor of $(2)^{1/2}$ over the previous estimates if the five readings are truly independent. Again, the results of this second test case are consistent with the estimated errors.

Based on the above results and analysis, we believe that this data reduction technique yields a reasonably accurate estimate of the angle of arrival variance. For all additional results reported in this paper, each data frame was read five times to provide smoothing. We estimate that this yields a one sigma read error in the root variance estimate of order 1 μm.

In the reduction of statistical data, a question of major importance is the residual fluctuations associated with the reduction of a finite data sample. This is a standard problem which is discussed in many texts. The parameters we calculate are the sample mean and sample variance.

$$\bar{r} = \frac{1}{N}\sum_{i=1}^{N} r_i, \tag{12}$$

$$\bar{\nu} = \frac{1}{(N-1)}\sum_{i=1}^{N} [r_i - \bar{r}]^2, \tag{13}$$

where N is the number of frames averaged and r_i are the smoothed image spacings. Assuming that the random variables r_i have the same mean (η) and variance (σ^2) and that they are uncorrelated, the expectations are[17]

$$E\{\bar{r}\} = \eta;\ \sigma_{\bar{r}}^2 = \sigma^2/N;\ E\{\bar{\nu}\} = \sigma^2. \tag{14}$$

Because we are calculating the sample variance, $\bar{\nu}$, the variance of $\bar{\nu}$ is required. Assuming that the variables r_i have the same fourth central moment (μ_4) and carrying out the required algebra yields

$$\sigma_{\bar{\nu}}^2 = \frac{1}{N}\left[\mu_4 - \left(\frac{N-3}{N-1}\right)\sigma^4\right]. \tag{15}$$

For Gaussian statistics this reduces to

$$\sigma_{\bar{\nu}}^2 = 2\sigma^4/(N-1). \tag{16}$$

[17] A. Papoulis, Probability, Random Variables and Stochastic Processes, (McGraw-Hill, N. Y., 1965), 245.

This result implies that the sample variance calculated via Eq. (13) should match the true variance of the statistical ensemble with a one sigma variation given by Eq. (16). Therefore, the "signal-to-noise ratio", defined as the estimate $(\overline{v})$ divided by the standard deviation of the estimate $(\sigma_{\overline{v}})$, is equal to $[(N-1)/2]^{1/2}$. Provided this number is large (compared with one), the signal-to-noise ratio for the sample standard deviation will be approximately twice this value.

The above analysis does not account for the effects of reading errors in the variance estimate. It can be shown that if these errors are Gaussian with mean zero, then Eq. (16) is multiplied by the factor $[1 + \sigma_E^2/M\sigma^2]^2$, where M is the number of independent readings of each frame and σ_E^2 is the variance of the (unaveraged) reading error. From Table 2 we estimate that σ_E^2 is of order 100 or less. In all cases reduced, σ^2 was in excess of 120, up to as large as 2500. With M = 5, this additional factor has a maximum value of order 0.17. Thus the effect of reading errors are not very significant in the final results. Of much more importance is the effect of the finite sample size which ranged from 50 to 100, yielding a signal-to-noise ratio of 5-7 in the variance and approximately 10-14 in the standard deviation.

3.5 RESULTS AND DISCUSSION

In all, we have reduced twenty data sets. The results are given in Table 3 and Figure 4. These data were taken on seven different nights over a span of nine days. Nine were taken outside the observatory ($\simeq$ 50 feet away), nine were taken inside the east dome and the other two were taken atop Red Hill.

In all cases except the first (ESB), 50 to 100 frames of data were processed. In some cases the reading error seemed to be somewhat greater than the values given in Table 2. This was probably due to excessive defocus which resulted in large underexposed images which were more difficult to read. However in line with the discussion of the previous section, we believe that residual fluctuations are dominated in all cases by the finite sample size. Hence we estimate the standard deviation (σ_r) signal-to-noise ratio to be of order 10. Therefore the minimum statistically significant difference between two measurements is at least 10%.

The value of (Δ/R) were calculated using Eq. (4). Due to the smallness of this factor in all cases, its effect was ignored when calculating the differential angle of arrival via Eq. (5).

The last column of the table gives theoretical values for the parameter (r_o) derived from the measurements using the theory discussed in Section 3.2. Use of the single component theory of Eqs. (6) - (11) requires an additional factor of two on the right side of Eq. (6) to account for the two dimensionality of the measurements. This assumes that the angle of arrival statistics are isotropic. In this case, the correlation function, C_{12}, is defined as $\langle \underset{\sim}{\alpha}_1 \cdot \underset{\sim}{\alpha}_2 \rangle / 2\langle \alpha^2 \rangle$, where $\langle \alpha^2 \rangle$ is the single component variance

TABLE 3. DIFFERENTIAL ANGLE OF ARRIVAL MEASUREMENTS

Run	Date; Time (local)	Location; θ_{El}^{o}	N	$\bar{r}$ (μm)	$\bar{\nu}^{1/2}$(μm)	$(\Delta/R) \times 10^{-3}$	$\left\langle (\alpha_1 - \alpha_2)^2 \right\rangle^{1/2}$ (μrad)	Derived r_o (cm)
ESB	8/22; 2340	Outside; ≈50	10	338	21	2.8	3.7	8.5
1-1	8/24; 2200	Outside; 67	49	442	26	3.7	4.5	6.8
2-1	8/24; 2300	Outside, 75	50	311	30	2.6	5.2	5.7
2-2	8/24; 2330	Outside; 68	50	297	21	2.5	3.7	8.5
3-1	8/24; 2415	Outside; 58	50	263	24	2.2	4.3	7.2
3-2	8/25; 2145	Outside; 65	72	372	33	3.1	5.8	5.0
4-1	8/25; 2230	Inside; 58	99	331	52	2.7	9.1	2.6
4-2	8/25; 2400	Inside; 55	79	270	41	2.2	7.2	3.8
5-1	8/25; 2430	Outside; 48	98	524	46	4.3	8.1	3.3
6-1	8/26; 2045	Inside; 60	79	210	22	1.7	3.9	8.1
6-2	8/26; 2130	Outside; 54	89	1192	28	4.4	4.9	6.1
7-1	8/27; 2100	Outside; 72	50	348	21	2.9	3.7	8.5
7-2	8/27; 2130	Inside; 68	49	309	18	2.6	3.2	10.3
8-1	8/29; 2030	Inside; 72	50	160	11	1.3	2.0	17.8
8-2	8/29; 2130	Inside; 68	50	140	12	1.2	2.1	16.7
9-1	8/29; 2200	Inside; 78	50	109	12	0.9	2.1	16.7
9-2	8/29; 2215	Inside; 75	50	89	13	0.7	2.3	15.2
10-1	8/30; 2045	Red Hill; 72	50	350	15	2.9	2.7	12.6
10-2	8/30; 2130	Red Hill; 68	50	378	14	3.1	2.5	13.9
11-1	8/30; 2245	Inside; 78	50	192	12	1.6	2.1	16.7

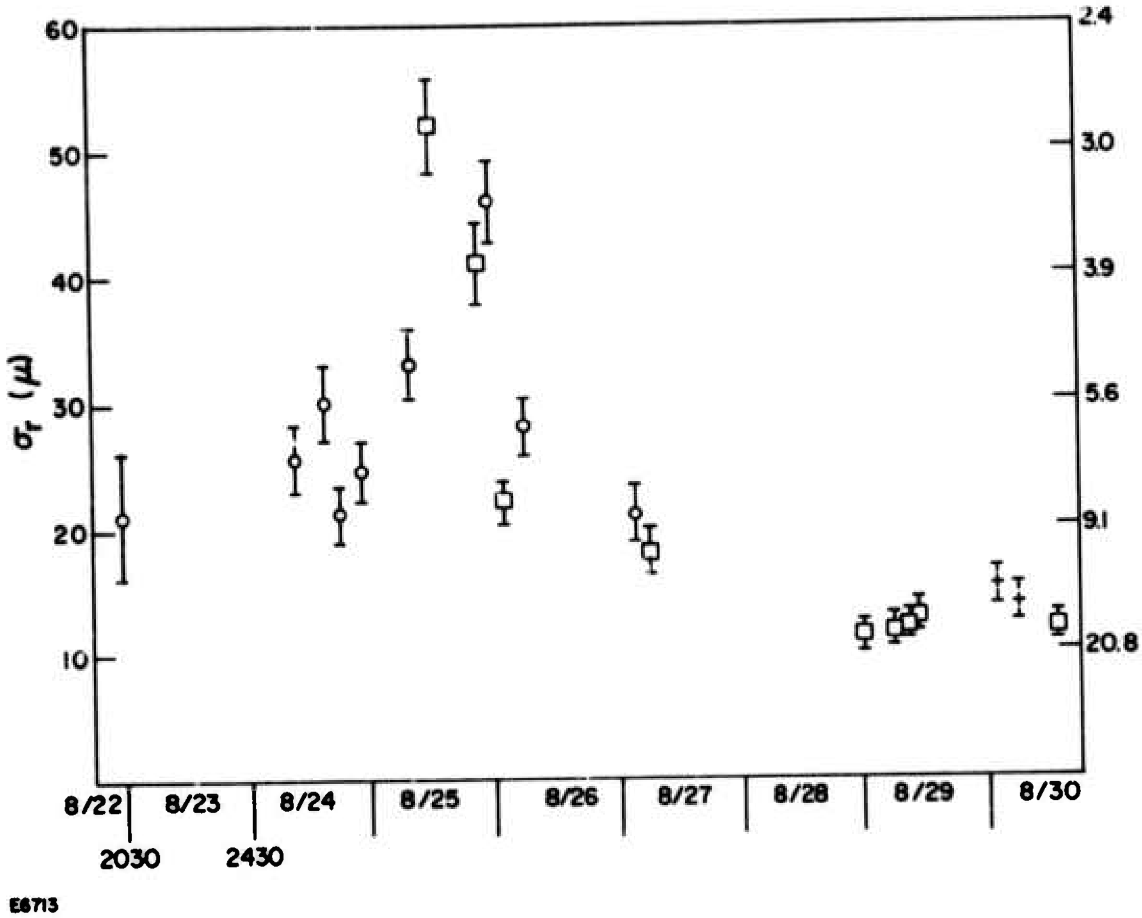


Figure 4 Measured Differential Angle of Arrival Standard Deviations and Derived Values of r_o. Locations of data collection are: O, outside observatory; □, inside observatory; +, atop Rea Hill. The bars indicated the estimated one σ spread in the data due to finite sample size.

of Eq. (7). With this definition $C_{12}(o) = 1$ and $C_{12}(\infty) = 0$, assuming zero mean. Substitution of Eqs. (7), (10) and (11) into Eq. (6) yields a factor of $\beta\,[1 - C_{12}]$. For a wavelength of 0.5 μm and pathlengths in the range of (10-20) km, neither condition on β (Eq. (11)) is fulfilled for an aperture of 2.25 inches. Thus an intermediate value of β should be used. Based upon subjective observation of the motion of the images in real time during the experiment we do not feel that the amount of correlation was high. The range for this factor is zero ($C_{12} = 1$) to one ($C_{12} = 0$, $\beta = 1$). Therefore we selected the midpoint value of 0.5. In view of the above observations, we feel that this particular value is more likely to be low. With $\lambda = 0.5\ \mu$m and d = 2.25", this results in the numerical relationship

$$r_o = 330\, \sigma^{-6/5} \tag{17}$$

where the units of σ and r_o are μm and cm, respectively.

Alternately, the theory developed by Fried[12] can be used to evaluate r_o. He evaluates the one dimensional variance in terms of a function $I(\mathcal{s},\phi)$ where $\mathcal{s}$ is the nondimensional space (S/d), and ϕ is the angle between the line joining the hole centers and the direction along which the variance is being evaluated. Numerical values for $\phi = 0$ and $(\pi/2)$ are given. Applied to our case of a normalized spacing of 2.1 and a two-dimensional variance yields

$$\left\langle (\underset{\sim}{a}_1 - \underset{\sim}{a}_2)^2 \right\rangle = \frac{3.44}{\pi^2} \frac{\lambda^2}{d^{1/3}\, r_o^{5/3}} \left[I(2.1, 0) + I(2.1, \pi/2) \right]$$

$$\simeq \frac{3.44}{\pi^2} \frac{\lambda^2}{d^{1/3}\, r_o^{5/3}} \tag{18}$$

This result is identical to Eq. (17). While this theory appears to give a more straightforward solution to the problem than the previous arguments, it does have several potential difficulties. Implicit in this evaluation is the assumption that $\beta = 1$. As discussed above, this is probably not the case for all separations of interest. The evaluation of $I(\mathcal{s},\phi)$ requires Eq. (10) to be valid out to a spacing of S + d. This may not be justified theoretically in all cases.[17] Finally, the numerical evaluation shows that $I(\mathcal{s}, o) + I(\mathcal{s}, \pi/2)$ is zero at $\mathcal{s} = 0$ (as required), increases to a maximum of 1.31 at $\mathcal{s} \simeq 9.5$ and then decreases monotonically, at least out to the largest values of $\mathcal{s}$ given (20). While such behavior cannot be ruled out for any fundamental reason, it is hard to understand physically. More importantly, the integral form shows that $I(\mathcal{s},\phi)$ grows without bound for large $\mathcal{s}$. This is clearly nonphysical because $I = (1 - C_{12})$ and should approach unity for large separation. Fried notes this limit, but does not comment on the range of validity of his results. Obviously this is another example of the problems which can be encountered when using the Kolmogorov spectrum without a low frequency cut-off.(16)

In summary, we have given two approaches to the determination of the relationship between r_0 and σ, with identical results. One is basically a plausability argument while the other is more theoretical. Both have certain problems. Clearly this is a fruitful area for future experimental measurements. Without these measurements, the results of Eq. (17) must be approached with caution.

The results of our data reduction show measured variances from 12 to 53 μm. Figure 4 shows a significant degradation in seeing conditions early in the experimental period. However conditions appear to have substantially improved by the last two nights. This wide variation over a short time ($\approx$ factor of four) was not entirely unexpected based on the subjective impressions of AMOS seeing conditions on the part of a number of visual observers. It is also interesting to note that the night-to-night variation in conditions was generally greater than variations measured in a single night. However we point out that all measurements were made between 2000 and 2430 hours local time and so we have no information regarding changing conditions over an entire night from dusk to dawn.

Eight data sets were taken with the specific objective of obtaining a comparative measure of seeing inside and outside the observatory. The procedure here was to take a data run in one location and then move the equipment to the other location as quickly as possible and take another run. The resulting four subsets (3-2 and 4-1; 5-1 and 4-2; 6-2 and 6-1; 7-1 and 7-2) yields only one case (3-2 and 4-1) where we feel there is a clear statistically significant difference in the measurements. These data are not consistent with a strong local effect. However this is a very limited amount of data upon which to base a conclusion. Also the observatory dome was cold since neither the telescope or any major systems inside the dome (except dome drive) were operational at the time the inside measurements were made. We expect to make further measurements of this type in the future. These will probably include true simultaneous measurements made with two instruments.

Four sets were taken with the objective of investigating any influence on seeing of the relative angle between the dome slot and the wind. During the time this data was taken the wind velocity was approximately 20 mph and steady from the east. For set 9-1, the slot was down wind while for set 9-2 it was up wind. For sets 8-1 and 8-2, the relative angle was approximately 45° and 135°, respectively. No statistically significant differences were seen. We note that these four data sets represent the best night of seeing during the entire measurement period.

The data taken on the last night (10-1, 10-2 and 11-1) are the only results involving measurements at Red Hill. They do not indicate any major differences between this location and the observatory.

Now consider the derived values of r_o which ranged from 2.6 to 17.8 cm. These values correspond to a variety of zenith angles. Theory[13] predicts a $(\cos \Theta_Z)^{3/5}$ dependence for r_o. Making this correction leads to a range of values for zenith from 3 to 18 cm with an average of 10.3 cm. We define a "seeing angle" as (λ/r_o) which yields a long exposure transfer function (Eq. (8)) of $\tau(r_o/\lambda) \simeq 0.03$. This definition yields a range of seeing angles (at $\lambda = 0.5\,\mu m$) from 0.6 to 3.4 arc seconds with an average of 1.3 arc sec.

The theoretical results of Kerr et al[6] are for single component angle of arrival variance over an aperture of 30 cm diameter and various levels of turbulence. For propagation downward through the entire atmosphere these results, (when adjusted for a decrease in aperture to 2.25") yield values from 0.5 to 3.6 μrad. These predictions cannot be compared directly with ours since they are not differential. Assuming the correlation predicted by Eq. (18) leads to a range for the two dimensional differential variance from 0.7 to 5.1 μrad. This is to be compared with our experimental results which range from 2.0 to 9.1 μrad. The experimental results of Lese[9] were reduced from the observation of the locations of multiple short exposure images of a star viewed with a 90 cm telescope. His two dimensional results ranged from 1.4 to 5.4 μrad with a mean of 3.0 μrad. From these values we infer a differential variance range from 2.2 to 8.5 μrad with a mean of 4.7 μrad.

A large number of theoretical predictions for r_o based on various atmospheric models have been made. In particular a value of 11.7 cm has been calculated[18] for zenith viewing at the AMOS site using the Hufnagel night model.[19] It does not appear that many measurements of r_o have been made for vertical propagation. Kelsall[20] reports MTF measurements made with a shearing interferometer on Haleakala using stellar sources. While he does not calculate a value of r_o, he does give experimental and theoretical[15] curves for the MTF. Although there are some differences in shape, the best fit seems to be with a theoretical curve corresponding to an r_o of approximately 3 cm. Very recently Dainty and Scaddan[21] have reported measurements of the long exposure transfer function using a coherence interferometer taken over a period of ten nights at the Mauna Kea Observatory on the island of Hawaii (approximately 75 miles southeast of AMOS). Twelve measurements are reported which they reduced using Eqs. (8) and (10). The resulting values of r_o range from 4.1 cm to 19.3 cm with an average of 12.7 cm.

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(18) G. Dryden, private communication.

(19) R. Hufnagel, Restoration of Atmospherically Degraded Images, Woods Summer Study, Vol. 2, App. 3 (DDC, Alexandria, Va., 1966).

(20) Kelsall, J. Opt. Soc. Am. 63, 1472 (1973).

(21) J. C. Dainty and R. J. Scaddan, Measurement of the Atmospheric Transfer Function at Mauna Kea, Hawaii, preprint.

In summary we believe that this technique can produce accurate and interesting information about the propagation of light through a turbulent medium. The results obtained to date appear to be of good quality and reasonable from the point of view of theory, other experimental results and the subjective impressions of visual observers at the site. One practical difficulty with it is the time required to reduce the data. We hope to overcome this difficulty by automating both the data collection and processing. Detectors could also be designed to measure the scintillation associated with each subaperture. This would result in a single instrument capable of obtaining both amplitude and phase information. In the future we plan to make additional measurements, including simultaneous measurements at two locations, in order to collect sufficient data to support definite conclusions about seeing characteristics at AMOS. Measurements of the spatial and temporal correlation functions will also be included. This information is required in order to determine the utility of this technique for evaluating the seeing conditions at potential sites of new large aperture telescopes.

4.0 CONTROL OF LOCAL TURBULENCE

4.1 GENERAL

The control of local turbulence effects is a subject which the astronomical community has been concerned with for some time. It appears that over a period of years a number of practices have been recognized as generally useful for combating these problems. However, current information indicates that careful experimentation designed to isolate various causes, effects and cures has not been carried out. Therefore, the utility or universality of any single method is not clearly understood. A contributing factor to this lack of detailed understanding may be the variations in construction, location and meteorlogical conditions from one observatory to another.

A number of these recommendations relate to the location, size and general features of observatories. Because the AMOS observatory exist, these are not of particular interest to this discussion. Of direct interest are recommendations regarding observatory operation and non-structural or minor structural charges. Most of these deal with thermal control in the form of the establishment of thermal equilibrium, elimination of local thermal sources and the positive control of air flow.

A number of authors have discussed effects related to the physical structure of observatories.[4, 22-24] The dome may trap considerable heat during the day which then dissipates during the night. In addition radiation cooling can also occur leading to further non-equilibrium effects. Specific suggestions regarding paint and insulation are considered useful in overcoming this problem.

Local heat sources interior to and below the dome are also important. As pointed out by Meinel,[4] even the emission by the human body ($\simeq$ 25 watts when quiescent) can be important. The heat dissipation associated with electrically powered instrumentation is also of concern.

Even when the above effects are minimized, some residual heat sources will inevitably remain. The heat generated by these sources will

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(22) J. Stock and G. Keller, in Ref. 4, 146.

(23) J. Rosch, in Proc of 14th Plenary Meeting of Cospar, Vol. II, Ed. by S.A. Bowhill, L.D. Jaffe and M.J. Rycroft (Akademie-Verlag, Berlin 1972), 1648.

(24) G.P. Kuiper, in Ref. 23, 1684.

usually escape through the open dome slot leading to turbulence in the optical path. To deal with this problem, ventilation fans in the dome and telescope are recommended.

Stock and Keller[22] and Rosch[23] discuss the design of instruments to minimize these effects. Most are combinations of ventilation and temperature control. Suggestions range from the use of temperature controlled metallic mirrors to the total evacuation of air from all parts of the optical system for which this can be done.[25]

4.2 SEEING CONSERVATION PROCEDURES AT THE MAUNA KEA OBSERVATORY

During July 1973, J. Heath (then an employee of Lockheed Missiles and Space Company, AMOS Phase II Operations and Maintenance Contractor) visited the University of Hawaii's Mauna Kea Observaotry on the island of Hawaii. The reason for his visit was to discuss local seeing control practices used at Mauna Kea. A summary of the information he obtained is as follows.[26]

1) Air from the Mauna Kea Observatory building complex is exhausted downwind with respect to the standard trade winds.

2) During operations, the University of Hawaii has created, via a large fan, an air flow into the dome. This air is also exhausted downwind.

3) A single large fan in the lower portion of the 88-inch telescope provides a continuous flow of air into the end of the enclosed tube.

4) The entire inside of the dome is insulated with approximately three inches of spray-on insulation.

5) Double doors seal off the dome from the rest of the building complex.

6) The University of Hawaii is sealing off all wiring ducts and air passageways that connect the building and dome.

7) The lights in the dome are only turned-on (during the day) when it is absolutely necessary.

8) A refrigeration system is used to keep the temperature of the major portion of the interior dome structure at or below the ambient temperature.

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(25) R.R. McMath, Sky and Telescope 14, 372 (1955).

(26) J.F. Heath, private communication. Also internal LMSC/Maui memo #L/OS-122 (10 August 1973) and AERL memo #A/OS-182 (9 January 1975).

Of the above items, some were not instrumental in improving the seeing at the Mauna Kea site. It is interesting to note that after the 88-inch telescope came into operation, local seeing effects were apparently creating an average seeing on the order of 4 arc seconds. The refrigeration system (8) and the insulated dome (4) were already installed at that time, as was the exhausting system (1). The remaining items were completed in a fashion that did not allow a determination of the sources of major improvement of seeing. However, the net effect was a substantial improvement in seeing with a median value for 1972 of order 1.5 arc sec.[27]

4.3 SEEING CONSERVATION PRACTICES AND PROCEDURES

Based on his study of this problem, Heath has made the following recommendation with regard to AMOS.

1) Control the air flow over the telescope mirror by use of an array of fans.

2) Stabilize the lower dome by opening the lower doors to ambient air.

3) Control air flow into the dome by use of a high capacity fan.

4) Seal all wiring trays and passageways with insulation.

5) Avoid opening the dome during the day and use lights only when necessary.

H. Kent[28] has also studied this problem (under the AMOS Phase II Scientifice and Technical Direction contract) and has identified the following deficiencies and corrective measures.

1) Thermally isolate the dome walls from air within the dome (cellular panels or foam-in-place insulation). Coat isolating layer with low thermal emissivity material, e.g., aluminum foil or aluminum paint ($\epsilon_{th} \leq 0.2$).

2) Institute "seeing" conservation procedures: minimize the number of warm bodies present and lossy electrical equipment and non-critical displays turned on in dome during obervations. Park late arriving cars (< 3 hours before mission) out of the expected LOS sweep or more than 150 meters from dome base.

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[27] Morrison, Murphy, Cruikstark, Sinton and Morton, Pub Ast. Soc. Pac. 85, 255 (1973).

[28] H. Kent, private commumication.

3) Fit the exterior dome cap with meridian fins to break up laminar wind flow thereby assuring good mixing and efficient cooling. Paint all with Titanox-RA2 or equivalent super white ($\alpha_s/\epsilon_{th} \simeq 0.2$).

4) Seal and refrigerate the dome during the day to the expected nighttime ambient temperature (40 to 45°F). This would require (worst case) pumping heat at 27 kW rate (92,000 BTU of air conditioning) and dehumidifying.

5) There is a body of professional opinion which favors heavy non-coniferous foliage around an observatory to reduce ground heating during the day. Leafy structures convert some impinging radiation to chemical energy, lose further energy by evaporation and equilibrate rapidly at night by virtue of high surface-to-mass ratio. Artificial ground cover for AMOS can be provided by use of white plastic film or cotton gauze. This "roof" should reduce ground heating and have a low heat capacity.

4.4 RECOMMENDATIONS

The discussion of Section 4.3 represent a fairly comprehensive set of recommendations dealing with the control of local seeing effects. Some of these are straightforward, simple and inexpensive to carry out. Others require greater expenditure. Since a well developed program to evaluate seeing characteristics at AMOS is presently underway, it seems advisable to await the outcome of these measurements before a full scale control effort is instituted.

However we feel that the forced air flow test (for overall control of air flow throught the dome) recommended by Heath[26] should be implemented. All that is required is a high capacity fan which can be placed at various locations in the upper and lower dome in order to investigate the possible existance of an optimum air flow pattern. The effects of ventilation can be quantified by simultaneous measurements made with the Seeing Monitor of RTAM. In addition, the microthermal sensors which will soon be operational at AMOS will be useful in obtaining a careful evaluation of this thermal control technique.

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